Estimating the BTeV potential for semileptonic decays

1 Introduction

Semileptonic decays of b and c hadrons can provide a wealth of information about the Standard Model. In particular, semileptonic decays can be used to determine CKM matrix elements as well as measure form factors. The matrix elements $|V_{cb}|$ and $|V_{ub}|$ can be obtained from $B \to D^{(*)}\ell\nu$ and $B \to \rho\ell\nu$ decays for instance. Measuring form factors provides information about how QCD affects weak decays. These form factors can also be compared between different decay modes and between b and c decays to check the theory behind SU(3) and HQET for example. In addition, semileptonic form factors are related to some rare decay modes which provide interesting windows to new physics.

Using techniques developed for fixed-target charm experiments (including E691 [1], E687 [2], and E791 [3, 4]) we demonstrate that BTeV has the necessary capability to extract information from semileptonic decays. Given the large number of b-hadrons reconstructed by BTeV, the semileptonic reach will be extraordinary.

2 Signal and background

The signal and background were generated using the MCFast Monte Carlo program. A full description of this program can be found elsewhere [5, 6]. MCFast is designed to be a fast and accurate detector simulation with speed and flexibility achieved through parameterization. The MCFast tracing includes the effect of magnetic fields, multiple Coulomb scattering, bremsstrahlung, dE/dx, decays in flight, pair conversions and secondary hadronic interactions. The simulation assumed a luminosity of $2{\times}10^{11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and included multiple interactions per event. The muon identification code used in this analysis starts by making an acceptance cut. Potential muon tracks must have momentum greater than 5 GeV/c. All tracks are projected through the three muon stations using the track parameters determined from the Kalman filter. If the projection misses any of the stations the track is thrown out. If the track is associated with a muon particle it is identified as a muon. If the track is not a muon then a misidentification probability is determined and a random number is generated to determine if the particle is misidentified as a muon.

The misidentification probability decreases as the momentum increases and decreases as the radius increases. The misidentification rate varies from 7% for 5 GeV/c tracks near the beam to 0.2% for 50 GeV/c muons at the outer edge of the muon system. The misidentification rate (away from the central region) is loosely based on the measured misidentification rate from the FOCUS experiment. FOCUS is a fixed-target charm experiment which used a ~180 GeV photon beam at a rate of approximately 10 MHz. BTeV and FOCUS have similar muon rates and momenta. The BTeV detector has two advantages over the FOCUS muon system. The BTeV detector has much finer granularity and the shielding is magnetized which, by allowing a momentum measurement, provides another handle to distinguish real muons from fakes.

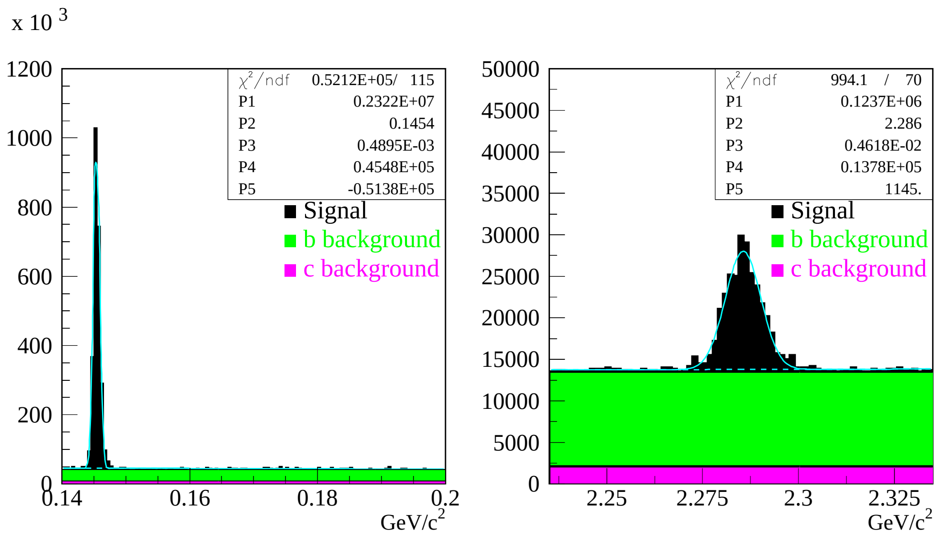
The signal modes analyzed in this study were $B^0 \to D^{*-}(\overline{D}^0(K^+\pi^-, K^+\pi^-\pi^-\pi^+)\pi^-)\mu^+\nu$ and $\Lambda_b^0 \to \Lambda_c^-(pK^-\pi^+)\mu^+\nu$. In each case, ~120,000 events were simulated. Three sources of background were simulated: minimum bias events, charm events, and generic b events (without the signal mode). The cross sections for minimum bias, charm, and b events obtained from Pythia [7] are shown in Table 2 along with the predicted numbers of events from one year (10^7 s) of running at a luminosity of 2×10^{32} cm^{-2}s^{-1}.

Table 1: Production cross sections and expected generation rates for signal and background. Cross sections for $b\bar{b}$ production are estimated from D0 data. Minimum bias cross section is estimated from assuming 2 interactions/crossing at $\mathcal{L} = 2\times10^{32}$ cm^{-2}s^{-1}. The charm cross section is assumed to be 1% of the minimum bias cross section. Branching ratios are from PDG00 [8] except $\Lambda_b \to \Lambda_c\mu\nu$ which is estimated at 4%.

Species	Quark cross section (mb)	Hadron fraction	Branching Ratio	Total produced/year ($\mathcal{L} = 2\times10^{32}$ cm^{-2}s^{-1})
Min bias	75	100%	100%	1.5×10^{14}
Charm	0.75	100%	100%	1.5×10^{12}
generic b	0.10	100%	100%	2.0×10^{11}
$B^0 \to D^*\mu\nu$	0.10	75%	0.35%	5.3×10^8
$\Lambda_b \to \Lambda_c\mu\nu$	0.10	10%	0.20%	4.0×10^7

Clearly it is impossible to simulate 10^{14} events given the current state of computing; simulating more than 10^8 events is prohibitive. Therefore we try to estimate the background based on a simulation of 4.2 million minimum bias events, 4.8 million $c\bar{c}$ events, and 1.5 million $b\bar{b}$ events. Given the large number of produced b-hadrons we can certainly make stringent cuts and still retain a large sample of events. Unfortunately, using these stringent cuts elminates nearly all of our (limited) background which makes it difficult to determine the significance or signal-to-noise ratio of the signal. Since the signals analyzed require detached vertices, reconstructed charm particles, and muons, we assume that the background will be dominated by c and b events, not minimum bias events. Therefore, we can safely tighten our cuts enough to eliminate all of the minimum bias events which were simulated.

Using these cuts keeps 4 (1) $c\bar{c}$ and 26 (13) $b\bar{b}$ events for the $B^0 \to D^*(D^0(K\pi, K3\pi)\pi)\mu\nu$ ($\Lambda_b \to \Lambda_c(pK\pi)\mu\nu$) decay mode. Figure 1 shows the result of scaling the signal and background events to one year of running at a luminosity of 2×10^{32} cm^{-2}s^{-1} and distributing the background events evenly through the mass plot. The yield, significance, signal-to-background, and efficiency is tabulated in Table 2. These results include a conservative trigger efficiency (50%) which is what is expected from the detached vertex trigger. A detached muon trigger is also planned which will increase the trigger efficiency.



(a) $D^*\!-\!D^0$ Mass diff ($B^0 \to D^* \mu\nu$) (b) $pK\pi$ Inv mass ($\Lambda_b \to \Lambda_c \mu\nu$)

Figure 1: (a) $D^* - D^0$ Mass difference distribution for $B^0 \to D^*(D^0(K\pi, K3\pi)\pi)\mu\nu$ signal events and $b\bar{b}$ and $c\bar{c}$ background events. (b) pKπ invariant mass distribution for $\Lambda_b \to \Lambda_c(pK\pi)\mu\nu$ signal events and $b\bar{b}$ and $c\bar{c}$ background events. In both plots, the background events have been spread evenly through the mass range.

3 Semileptonic reach

To determine the form factors associated with a particular semileptonic decay we would like to have all the kinemtic information associated with the decay chain. The most important quantity is q^2 which is the square of the virtual W mass; i.e. the invariant mass of the lepton and neutrino. Reconstructing the momentum vector is not a trivial exercise, however. The technique used to reconstruct the neutrino momentum, pioneered by E691 and used by E687 and E791 among others [1, 2, 3, 4], is particularly suited to BTeV as it requires good vertex resolution compared to the vertex separation. The production and decay vertex of the b-hadron gives the b-hadron momentum vector direction. The neutrino momentum per-

Table 2: Efficiency, expected yields, signal-to-background, and significance in one year of running at a luminosity of $2 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Efficiency includes acceptance, trigger efficiency, reconstruction efficiency and cut efficiency. Significance and signal-to-background are calculated by integrating over a $\pm 2\sigma$ region around the mass peak.

Decay mode	Efficiency	Yield	$S/\sqrt{S+B}$	S/B
$B^0 \to D^*(D^0(K\pi, K3\pi)\pi)\mu\nu$	0.44%	2,300,000	1,430	21
$\Lambda_b \to \Lambda_c(pK\pi)\mu\nu$	0.31%	120,000	210	1.0

pendicular to the b-hadron momentum vector is easily measured because it must balance all of the other decay products. The neutrino momentum parallel to the b-hadron momentum can be determined (up to a quadratic ambiguity) by assuming the invariant mass of the b-hadron. We pick the low momentum solution for the parallel component of the neutrino momentum as Monte Carlo studies indicate this is correct more often.

The most recent published results using this method come from E791 [4]. Using a 500 GeV/c π^- beam, they reconstruct over 6,000 $D^+ \to \overline{K}^{*0}\ell\nu$ decays. From this sample they obtain form factor measurements of $r_V = V(0)/A_1(0) = 1.87 \pm 0.08 \pm 0.07$ and $r_2 = A_2(0)/A_1(0) = 0.73 \pm 0.06 \pm 0.08$. From the 3,000 muon decays, they also measure $r_3 = A_3(0)/A_1(0) = 0.04 \pm 0.33 \pm 0.29$. Defining the q^2 resolution as the RMS of the generated q^2 minus the reconstructed q^2 divided by q^2_{max}, E791 had a q^2 resolution of 0.17. From the MCFast simulation with the standard selection criteria and reconstructing the neutrino momentum as described above, BTeV has a q^2 resolution of approximately 0.14 as shown in Fig. 2. With 6,000 events, the E791 results give smaller errors than most lattice QCD calculations. With a similar q^2 resolution and 100 times more data, BTeV will also be able to challenge theoretical predictions or provide values which can be input into other calculations.

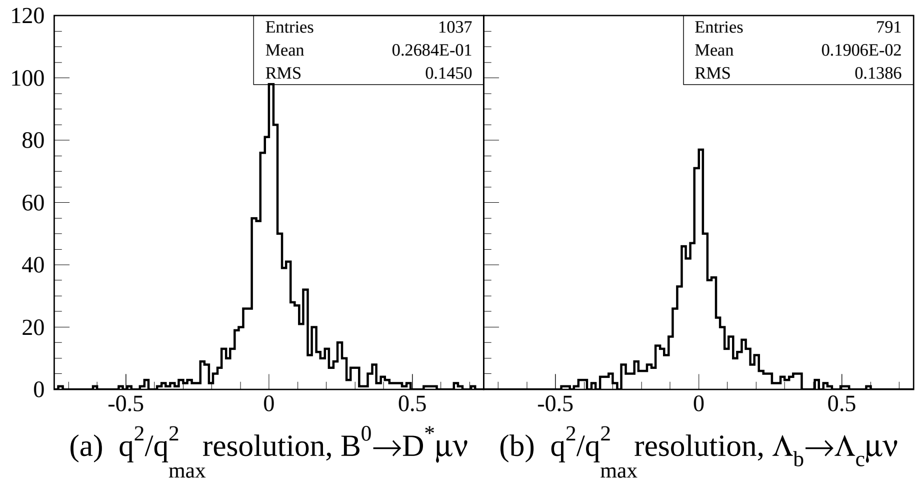


Figure 2: q^2/q^2_{max} resolution for (a) $B^0 \to D^*(D^0(Kn\pi)\pi)\mu\nu$ and (b) $\Lambda_b \to \Lambda_c(pK\pi)\mu\nu$.

One additional difficulty in extracting information from these semileptonic decays comes from b semileptonic decays into charm excited states which decay into the state being investigated. For example, in the decay $\Lambda_b^0 \to \Sigma_c^+ \mu\nu$, the Σ_c^+ can decay to $\Lambda_c^+ \pi^0$. Assuming the π^0 is lost, this event will be reconstructed as a signal $\Lambda_b^0 \to \Lambda_c^+ \mu\nu$ event and the neutrino reconstruction (which assumes the invariant mass of the $\Lambda_c^+ \mu\nu$ is equal to the Λ_b^0) will be inaccurate. The q^2 resolution for these events is shown in Fig. 3a. Assuming an equal mixture of $\Lambda_b \to \Lambda_c$ and $\Lambda_b \to \Sigma_c$ decays gives the q^2 resolution shown in Fig. 3b. This shows a resolution only slightly degraded (0.14 to 0.15) but with a bias equal to 1/3 of the RMS. BTeV has excellent π^0 reconstruction capabilities [6] which should make it possible to measure the relative branching ratios and correct for this bias.

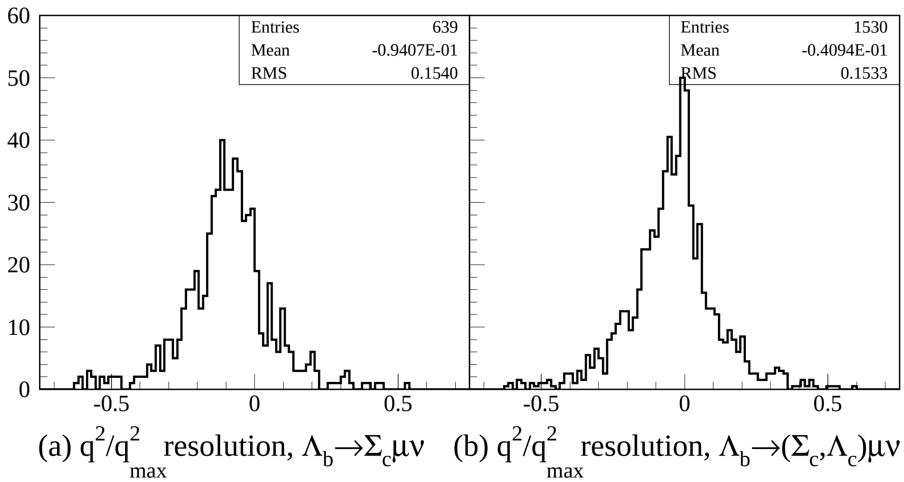


Figure 3: q^2/q^2_{max} resolution for (a) $\Lambda_b \to \Lambda_c(pK\pi)\mu\nu$ where the Λ_c comes from a Σ_c and (b) $\Lambda_b \to \Lambda_c(pK\pi)\mu\nu$ where half of the Λ_c's come from Σ_c's and half come directly from Λ_b's.

4 Conclusion

This study only provides a cursory look at some of the semileptonic physics available with BTeV. There are many other semileptonic decay modes of b-hadrons which are well within the grasp of BTeV. These decay modes include $B \to \rho\ell\nu$ to determine V_{ub} and B_s semileptonic decay modes to check SU(3). In addition, BTeV will have many semileptonic charm decays available for study.

References

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